Erbium doped optical waveguide amplifiers on silicon

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Introduction

Thin film integrated optics is becoming more and more important in optical communications technology. The technology for the fabrication of passive devices such as planar optical waveguides, splitters, and multiplexers is now quite well developed, and devices based on this technology are now commercially available. One next step to further improve this technology is to develop optical amplifiers that can be integrated with these devices. [1,2] Such amplifiers can serve to compensate for the losses in e.g. splitters or other components, and can also serve as pre-amplifiers for active devices such as detectors.

In optical fiber technology, erbium-doped fiber amplifiers[3,4] are now used in long-distance fiber communications links. They use an optical transition in Er^{3+} at a wavelength of 1.54 µm for signal amplification, and their success has set a standard of optical communication at this wavelength. Using the same concept of Er-doping, planar waveguide amplifiers are now being developed. For these devices silicon is often used as a substrate, so that opto-electronic integration with other devices in or on Si (electrical devices, or Si based light sources, detectors, modulators) may become possible. Fig. 1 shows an example of a silicon based optical integrated circuit[5] in which a 1×4 splitter is combined with an amplifying section.

At first sight, it may seem straightforward to translate the concept of a fiber amplifier to that of an integrated planar waveguide. However, in scaling down the device dimensions from the long fiber length (typically 40 m) to the small device dimensions of an opto-electronic integrated circuit, the Er concentration has to be increased to achieve the same amount of optical gain. As it turns out, physical processes that were unimportant in fiber technology become important in planar amplifiers.

In the past few years, several Er-doped planar optical waveguide materials have been explored, and in some cases optical gain has been achieved. The challenge today is to understand the processes that limit the gain, and to find materials and structures in which these processes have a minimum effect. This article discusses the most important of these processes, and gives an overview of the planar optical amplifiers obtained on silicon to date.

Principle of operation

In most materials, erbium assumes the trivalent charge state (Er^{3+}) with an electronic configuration of $[Kr]\cdot 4d^{10}\cdot 4f^{11}\cdot 5s^2\cdot 5p^6$. Spin-spin and spin-orbit coupling in the incompletely filled 4f shell give rise to a number of energy levels as depicted in Fig. 2. Each degenerate level is Stark-split into a manifold of levels, due to the presence of the host material. The transition from the first excited state ($^4I_{13/2}$) to the ground state ($^4I_{15/2}$) occurs at a wavelength of approximately 1.54 µm. The emission wavelength is relatively insensitive to the host material, because the 4f shell is shielded from its surroundings by the filled 5s and 5p shells.

In an optical amplifier, erbium is incorporated in the core of an optical waveguide. Using an external laser, the Er is excited into one of its higher lying energy levels. Erbium can be pumped directly into the first excited manifold using a 1480 nm diode laser, or via one of the higher lying absorption lines, for example using a 980 nm diode laser. In the latter case, the Er relaxes rapidly into the first excited state. When sufficient pump power is applied, this leads to population inversion between the first excited state and the ground state. A 1.54 µm signal travelling through the Er doped waveguide will then induce stimulated emission from the first excited state to the ground state, resulting in signal amplification.

Waveguide fabrication

In order to fabricate an Er doped planar waveguide amplifier on Si, one needs to use a material that a) is *transparent* to the wavelength used to excite the Er, and to the signal wavelength, b) can *dissolve* large amounts of Er that is *optically active* (i.e. luminescent at high quantum efficiency), and, c) can be made into a *channel waveguide* using a technology that is compatible with standard Si processing. A number of waveguide structures can be used to realize a planar optical waveguide amplifier, each with their own specific advantages. In all of these structures, light is guided in a high refractive index material (*the waveguide core*), surrounded by a lower index material (*the cladding*).

Figure 3 schematically shows cross sections of different waveguide structures that can be used. A *channel waveguide* (Fig. 3a) can be formed by depositing a high index layer on a low index cladding, followed by standard lithography to define a line. The lithography is usually followed by the deposition of a low index top cladding. Another way of forming such a channel waveguide is by *ion implantation*. In this case the refractive index contrast is achieved by a change in chemical composition, or by ion irradiation induced damage.[6] A variation on the channel waveguide is the *ridge waveguide* (Fig. 3b), in which the high refractive index core layer is not fully etched back. This lowers the in-plane index contrast, and therefore in general decreases the scattering loss. Optical mode confinement can also be obtained by putting a strip of cladding material on a planar core layer, resulting in a *strip loaded waveguide* (Fig. 3c). This type of structure requires no etching of the Er doped core layer, thus leaving the Er unaffected by the waveguide fabrication process. Another structure is the *diffused waveguide*, formed

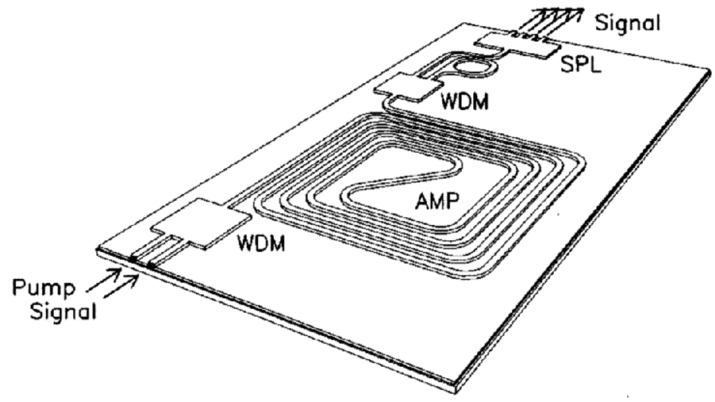

Figure 1: Example of an integrated optical circuit on silicon from Ref. 5. The 1.54 μm signal first enters a wavelength division multiplexer (WDM), where it is combined with a 1.48 μm pump beam that serves to excite the Er^{3+} ions in the amplifying waveguide (AMP), which is rolled up to reduce the size of the circuit. After being amplified by stimulated emission, the signal is decoupled from the pump beam in a second WDM. Using a 1×4 splitter the signal is then divided into four channels with an intensity equal to the input intensity. The remaining pump light is looped back into the amplifier.

by in-diffusing an element that raises the refractive index (Fig. 3d). Similarly, index contrast can be achieved using an ion exchange process,[7] in which ions in the core material are exchanged for ions from the salt melt in which the waveguide is immersed. The resulting low index contrast waveguides have low losses, due to the smoothly graded refractive index profiles.

As the light guiding in all these structures relies on total internal reflection, waveguide bends cannot be made infinitely sharp. The index contrast between core and cladding layers determines the minimum bending radius of a waveguide. For example, silica waveguides with a small refractive index contrast ($\Delta n \approx 0.01$) have a minimum bending radius in the centimeter range. Therefore long silica based waveguide amplifiers sometimes require a 4" wafer as a substrate.[8] For a high contrast waveguide, e.g. an Al_2O_3 core with an SiO_2 cladding ($\Delta n \approx 0.20$), the bending radius can be as low as 50 μm.[9] For such a system, it has been shown[10] that a 3 cm long waveguide can be 'rolled-up' on an area of only 1 mm^2. Consequently, if high integration densities are required, the core material must have a high refractive index. This high index contrast also results in smaller optical mode dimensions. Therefore, high pump intensities can be achieved at relatively low pump powers, decreasing the pump threshold for amplification.

Gain limiting processes and parameters

Erbium concentration and solubility

The most important parameter for amplification is the concentration of Er^{3+} ions that are optically active (i.e. that have high quantum efficiency). The maximum gain per unit length is determined by the product of the cross-section for stimulated emission σ_{em} and the active Er concentration. Since typical values for σ_{em} are in the 10^{-21}-10^{-20} cm^2 range, concentrations of 10^{19}-10^{20} Er/cm^3 are required to achieve a reasonable gain over a length of a few centimeters. Therefore, the host material must have a high *Er solubility.*

Silica based glasses have turned out to be a practical host material, as the composition can be tuned continuously for optimum Er solubility using various available network modifiers. It has been shown that by incorporating for example phosphorous in the glass matrix, the solubility of Er may be increased.[11] Aside from glasses, ceramic materials with a high refractive index, such as Al_2O_3 and Y_2O_3, are interesting hosts. As their crystal structure is similar to that of Er_2O_3, they show a high Er solubility.[12-14]

Waveguide loss

A next important parameter is the *waveguide loss*, determined by absorption and scattering of guided light. To achieve net amplification, the signal loss due to these intrinsic waveguide losses first has to be compensated for by stimulated emission. Moreover, at the Er concentrations needed to compensate for a typical waveguide loss of 1 dB/cm, Er-Er interactions reduce the gain, as will be discussed below. Pump light is also scattered as it travels through the waveguide, lowering the pumping efficiency. Thus, minimizing waveguide loss is crucial for good amplifier performance.

Scattering can be induced by irregularities in the refractive index on a length scale of the order of the wavelength. One notorious origin of scattering is waveguide roughness, caused for example by an etching step in the fabrication process. This effect becomes more pronounced when high index contrast structures are used.

Mode overlap

For optimum gain, both signal light and pump light should be confined in such a way that optimum overlap between the optical modes and the Er concentration profile is achieved. For low refractive index contrast materials, a significant fraction of the optical mode travels through the undoped cladding material, resulting in a lower gain per unit length.

Pump wavelength

Erbium doped waveguide amplifiers are either pumped at 980 nm (the $^4I_{11/2}$ level) or 1480 nm (the $^4I_{13/2}$ level). Pumping high into the first excited state of Er using a 1480 nm laser results in a quasi three level system, with a good overlap of the signal mode at 1530 nm with the pump mode, due to similar mode sizes at these wavelengths. Furthermore, scattering losses of waveguides usually increase going to shorter wavelengths, favoring a long wavelength pump laser. However, due to the overlap of the 1480 nm pump wavelength with the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ emission spectrum, the pump also induces stimulated emission at 1480 nm. This effect puts an upper limit to the degree of population inversion that can be obtained.

Stimulated emission by the pump is much weaker when a pump wavelength of 980 nm is used. In this case the excited Er rapidly relaxes non-radiatively into the first excited state, precluding stimulated emission by the pump from the 980 nm level. However, the internal relaxation also reduces the pumping efficiency, as the relaxation energy (about 0.45 eV per excitation event) is transformed into heat. In general, the absorption cross-section for the 980 nm level is smaller than that of the 1480 nm level, resulting in an increased threshold power.

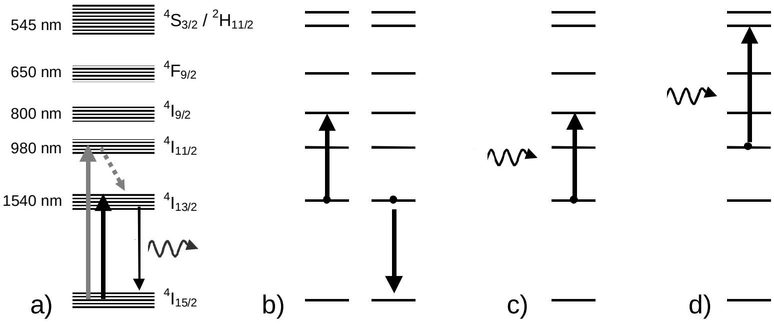

Figure 2: Schematic representation of the Er^{3+} intra 4f energy levels. Figure a) shows the 1.54 μm transition, and the upward arrows indicate excitation using 1480 nm pump light and 980 nm pump light respectively. Figure b) show the process of co-operative upconversion, where interaction between two excited Er^{3+} ions leads to the population of higher lying energy levels. Figure c) and d) show the process of excited state absorption of a 1480 nm or a 980 nm pump photon respectively.

Pump absorption

Due to the relatively small absorption cross-section of the Er energy levels, rather high pump intensities are required to achieve population inversion. This problem can be overcome by introducing Yb^{3+} ions into the Er doped waveguide. The Yb ions have a large absorption cross-section around 980 nm, and can transfer their energy non-radiatively to the $^4I_{11/2}$ erbium level.[15] As the Yb absorption band extends all the way from 850 nm to 1020 nm, it can be pumped over a broad spectral range.

Co-operative upconversion

At high Er concentrations, interaction between Er ions is an important gain limiting effect. One of such processes is *co-operative upconversion.* [1,16,17] In this process, an excited Er ion de-excites by transferring its energy to a neighboring excited ion, promoting it into the $^4I_{9/2}$ level (Fig. 2b). This lowers the amount of excited Er, or conversely, increases the pump power needed to obtain a certain degree of inversion. Co-operative upconversion is possible due to the presence of a resonant level at twice the energy of the first excited state. The co-operative upconversion coefficient depends on the host material, as it is related to the exact energy level positions, cross-sections, the dielectric constant, and the typical phonon energy of the host material. In practice, co-operative upconversion is an important gain limiting effect for Er concentrations above 10^{19} - 10^{20} Er/cm^3.

The effect of co-operative upconversion also depends on the microscopic distribution of Er ions in the host material. A clear illustration of this effect is given in Fig. 5, which shows a top view, taken with a CCD camera through an optical microscope, of two similar polycrystalline Al_2O_3 ridge waveguides, both doped to an Er concentration of 3×10^{20} Er/cm^3. The waveguides are pumped at a coupled power of 10 mW using a 1480 nm diode laser. The waveguide in Fig. 5a has been fabricated using Er ion implantation into Al_2O_3,[10] while the waveguide in Fig. 5b has been fabricated by radio frequency sputtering from a Er_2O_3/Al_2O_3 hot-pressed powder target.[18] The green light emission from both waveguides occurs at a wavelength of 545 nm. This luminescence is caused by a transition from the $^4S_{3/2}$ level, which is populated by a second order co-operative upconversion process, to the ground state.[16] Although the pump power and Er concentration in both waveguides are the same, the green emission in the Er co-sputtered film is much stronger. The higher amount of upconversion for co-sputtered material is attributed to the fact that co-sputtering takes place in form of Er_2O_3 clusters or molecules, while the ion implantation process leads to an even distribution of Er in the Al_2O_3 host. The upconversion strongly affects the amplifying performance. In fact, the implanted waveguide shows a net internal gain[10] of 2.3 dB, while the Er co-sputtered waveguide does not show net gain.[18] Therefore, in order to fabricate an efficient amplifier, the fabrication method should be optimized to obtain an homogeneous distribution of Er ions. Although upconversion is an unwanted effect for 1.54 µm signal amplifiers, it may be used advantageously for the fabrication of upconversion lasers, operating in e.g. the green.

Excitation migration and non-radiative quenching

An excited Er ion can transfer its energy to a nearby, unexcited Er ion. This *excitation migration*[19] does not necessarily reduce the Er population density, but can become detrimental to the gain if some Er ions are strongly coupled to non-radiative quenching sites. For example, the OH stretch vibration is resonant with the transition from the first excited state to the ground state of Er. Indeed, it has been shown that the Er luminescence lifetime correlates with the water content in silica glasses.[20,21] The effect of quenching sites becomes more pronounced at high Er concentrations, resulting in a reduced pumping efficiency. Therefore, care must be taken to synthesize Er-doped materials that are free of impurities or defects that couple to Er.

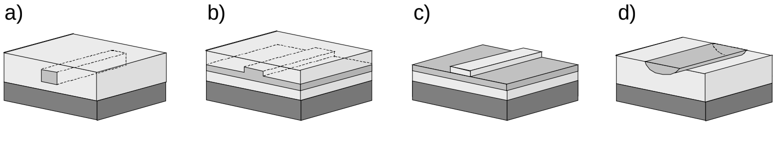

Figure 3: Schematic representation of waveguide structures that may be used to fabricate a planar optical waveguide amplifier. Light is confined in the high refractive index waveguide core (dark grey) by total internal reflection. The Er doped core material is embedded in a low refractive index cladding layer (light grey). The device rests on a silicon substrate (dark grey). Indicated are a channel waveguide (a), a ridge waveguide (b), a strip loaded waveguide (c), and a diffused waveguide (d).

Excited state absorption

Another gain limiting effect is formed by *excited state absorption* (ESA). In this process, an excited Er ion absorbs a signal photon (Fig 2c), or a pump photon (Fig 2c and Fig. 2d), bringing it in a higher excited state. As this effect involves both signal and pump photons, it affects both the maximum gain and the pump efficiency. The effect becomes important for the gain when the higher lying states have an appreciable lifetime, leading to the buildup of significant steady state population in the higher lying energy levels, which do not take part in the amplification. As ESA depends on the pump intensity, it becomes important when high pump powers are required, for example to compensate for co-operative upconversion processes, or de-excitation of the Er by strong signals.

The effect of ESA on amplifier performance is illustrated in Fig 4a. It shows the fraction of excited Er ions in a 17 cm long Er doped Al$_2$O$_3$ waveguide, calculated in the plane of the waveguide as the structure is pumped with 100 mW at 1480 nm. The Er doped waveguide core consists of a 2 μm wide, 520 nm thick ridge, with a remaining thickness on the sides of 260 nm (see Fig. 3b). The optical modes are centered in the ridge, but also extend into the Er doped sides, causing excitation outside of the waveguide core. The calculation takes into account the measured upconversion coefficient[16] and Er absorption and emission cross-sections,[22] as well as the three-dimensional 1480 nm pump and 1530 nm signal mode distributions. The effect of ESA is seen as a dip in the population in the region where the pump power is highest (in the center of the guide near the entrance facet). The effect on the differential signal gain across the guide is shown in Fig. 4b. It shows that at a pump power of 100 mW, ESA causes net signal loss. As the pump power decreases along the waveguide, the effect of ESA decreases, and initially the differential gain along the length of the waveguide increases. Absorption (by Er and the waveguide structure) and scattering lead to a gradual decrease of pump power along the waveguide, and near the end of the waveguide the pump power becomes too low to obtain a positive differential gain. The existence of an upper limit on the pump power, shows that ESA puts a maximum to the length that can be used for a single-end pumped waveguide.

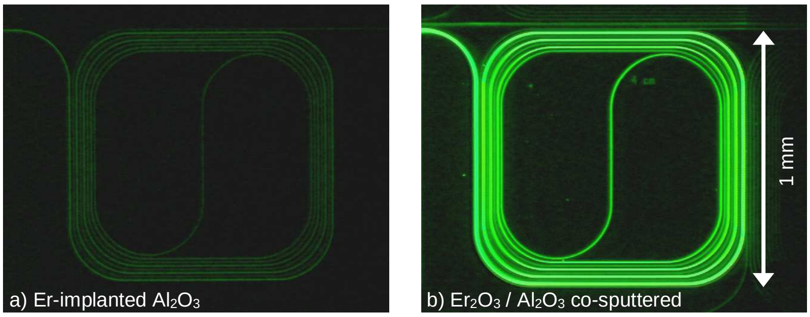

Figure 5: Top view of two similar Al$_2$O$_3$ miniature planar waveguide amplifiers on Si, pumped at 1480 nm at a power of 10 mW in the waveguide. The 3 cm long waveguides are rolled up on an area of only 1 mm^2. The waveguide in a) is fabricated using Er ion implantation,[10] the one in b) by Al$_2$O$_3$ / Er$_2$O$_3$ co-sputtering.[18] The green emission is due to a second order upconversion process in which energy is exchanged between excited Er ions. Upconversion is much stronger in the co-sputtered film than in the implanted film, which is attributed to the fact that implantation leads to a more homogeneous Er distribution than co-sputtering. The implanted waveguide shows net optical gain, the sputtered one does not.

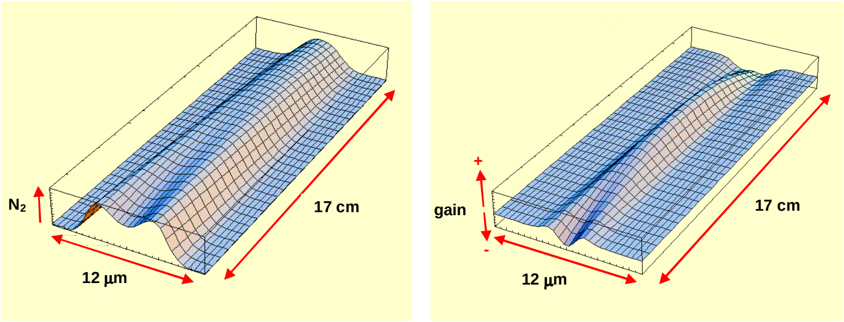

Figure 4: a) Fraction of Er in the first excited state along a 2 μm wide, 17 cm long ridge waveguide, calculated in the plane of the waveguide. The waveguide is pumped with 100 mW at 1480 nm. The maximum fraction of excited Er that is reached is 68 %. The dip near the front facet is caused by excited state absorption. b) Differential gain calculated from the excited Er distribution and the optical mode of the signal.

The state of the art in Er doped planar amplifiers

Although many research groups are studying Er doped optical waveguide materials, only a very limited number of groups has fabricated actual devices. Table I lists the most successful Er doped waveguide amplifiers on silicon that have been fabricated to date. In all cases, the waveguide materials were deposited on an oxidized silicon substrate.

A 43 cm long planar waveguide amplifier on silicon developed by Hattori *et al.* at *NTT Opto-electronics Laboratories*. (Japan), contains a phosphorous doped silica based glass as a core material.[8,23] The waveguides were fabricated by flame hydrolysis deposition, followed by reactive ion etching to form the ridge or channel waveguide. The amplifier shows an internal gain of 27 dB using a 980 nm pump power of 268 mW. A low Er concentration[24] of ~4×10^{19} Er/cm^3 (0.45 wt.%) was used, and was sufficient to achieve net gain, because the waveguide loss in this material is very low (0.15 dB/cm). As a result of this low waveguide loss, it is relatively easy to keep the pump intensity above threshold over a large distance along the waveguide, thus allowing for a large total gain. The combination of the large length and the low index contrast however, cause that a large surface area is needed to support the device.

Ref. *(et. al)*	Hattori[8]	Shmulovitz[13]	van den Hoven[10]	Barbier[27]	van Weerden[29]	Yan[30]
date published	5-94	4-96	4-96	2-97	4-97	11-97
waveguide core composition	P-doped SiO_2	soda-lime silicate glass	Al_2O_3	Yb co-doped phosphate glass	Y_2O_3	$P_2O_5/Al_2O_3/Na_2O/La_2O_3$
internal gain (dB)	27	~ 6.5	2.3	> 16.5	6.0	4.1
Er concentration (10^{20} cm^{-3})	~ 0.4[24]	0.7	2.7	~ 16[24]	1.3	5.3
length (cm)	47.7	6	4	9	4.3	1
gain / length (dB/cm)	0.6	1.1	0.6	> 1.8	1.4	4.1
pump power (mW) *=inside waveguide	264	80	9*	200	12*	21*
pump wavelength (nm)	980	980	1480	983	1480	980
waveguide geometry	ridge or channel	ridge or channel	ridge	channel	ridge	strip
core index of refraction	~ 1.46	~ 1.49	1.64	-	1.9	1.53
waveguide loss (dB/cm)	0.15[8]	0.1	0.35	~ 0.1	0.8	0.9

Table I: Characteristics of Er doped planar optical waveguide amplifiers operating at 1.54 μm that have been fabricated on silicon to date

At *Lucent Technologies / Bell Labs* (USA), Shmulovitz *et al.* fabricated a 6 cm long Er doped soda lime silicate glass based waveguide amplifier using radio frequency sputtering.[25,26] A ridge or channel waveguide was formed using ion beam etching. A fiber-to-fiber gain of 4.5 dB was measured at 80 mW of 980 nm pump light. The low background loss in this glass (0.1 dB/cm) allows for the use of a relatively low Er concentration (7×10^{19} Er/cm^3), reducing the effect of co-operative upconversion.

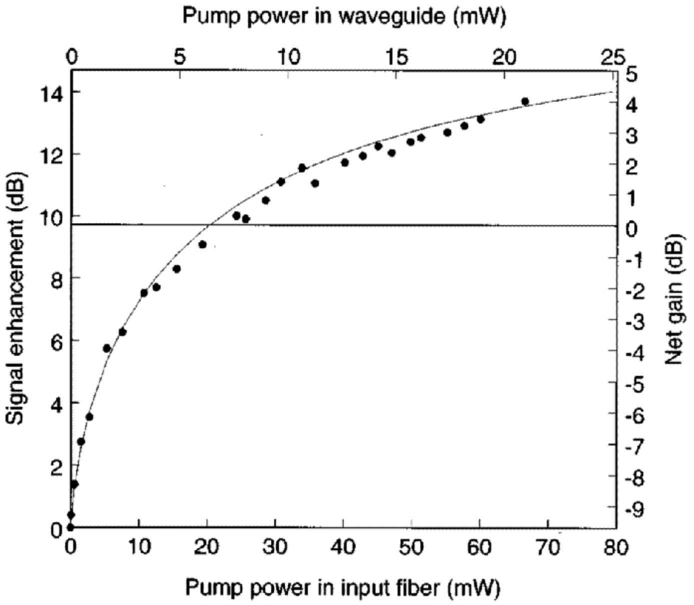

Figure 6: Small signal gain measurement on a 1 cm long Er doped phosphate glass waveguide amplifier on Si, taken from Ref. 30. When no pump power is applied, about -10 dB (10%) of the 1.54 μm signal is transmitted, due to waveguide losses and absorption by unexcited Er. At about 7 mW of 980 nm pump power in the waveguide (20 mW in the tapered input fiber), these losses are overcome by stimulated emission from the Er. At 21 mW pump power in the guide, a net gain of 4.1 dB is reached. The drawn line is a calculation taking into account the effect of co-operative upconversion.

A 4 cm long Er doped Al_2O_3 waveguide amplifier on Si was developed by van den Hoven *et al.* in a collaboration of the *FOM Institute for Atomic and Molecular Physics* and the *Delft University of Technology* (the Netherlands). The Al_2O_3 was deposited using RF sputtering, and doped with Er using ion-implantation. Argon beam etching was applied to create a ridge waveguide. A total internal gain of 2.3 dB was measured at a coupled pump power of 9 mW at 1480 nm.[10] The pump threshold of this device is only 3 mW, which is due to the high mode confinement in the high index Al_2O_3 core (n=1.64). As a result of this high index contrast, 3 cm interaction length could be fitted on an area of only 1 mm^2 (see Fig. 5). Up to now, this is the only demonstration of a miniature planar optical waveguide amplifier on Si.

Due to the high Er solubility in Al_2O_3, concentrations of optically active Er up to 3×10^{21} Er/cm^3 (3 at.%) could be incorporated in this material.[12] However, at such high concentrations, excitation migration and co-operative upconversion strongly decrease the steady state Er population. It was found that optimum amplifier performance was achieved at 2.7×10^{20} Er/cm^3. Calculations indicate that an internal gain around 20 dB may be achieved in a 15 cm long device, using around 40 mW of 1480 nm pump power.[10]

At *GeeO* (France), Barbier *et al.* developed a waveguide amplifier on Si showing a fiber to fiber gain of 16.5 dB over a length of 9 cm when pumped with 200 mW at 980 nm.[27,28] This was measured in an

Er-Yb codoped phosphate glass, in which a channel waveguide was formed using a two step ion-exchange process. The high gain is due to the high concentration[24] of ~1.6×10^{21} Er/cm^3 (2 wt.%) that was dissolved in the phosphate glass. Pumping of the Er is achieved via Yb^{3+}, resulting in a threshold pump power around 25 mW. Net gain was measured for wavelengths ranging from 1520 nm to 1570 nm, showing the potential of Er doped planar waveguide amplifiers as broadband optical amplifiers.

Another high index waveguide amplifier on Si was developed by van Weerden *et al.* at the *Twente University of Technology* (the Netherlands). Their Er doped polycrystalline Y_2O_3 waveguide amplifier shows 6 dB internal gain at only 12 mW pump power in the waveguide.[29] The core material was sputter deposited, and a ridge structure was defined by Ar ion beam etching. The relatively high waveguide loss of 0.8 dB/cm is compensated for by the high concentration of Er that can be incorporated in Y_2O_3.

The highest gain per unit length at low pump power was achieved very recently by Yan *et al.* An Er doped phosphate glass waveguide amplifier was developed, in a collaboration between *TNO-TPD* and *the FOM Institute for Atomic and Molecular Physics* (the Netherlands). The waveguide film was deposited by RF sputtering from a Er doped multi-component phosphate glass. Strip loaded waveguides were formed by etching of the SiO_2 top cladding layer. A net gain of 4.1 dB is achieved over a 1 cm waveguide, at a coupled pump power of 21 mW at 980 nm.[30] A gain measurement on this waveguide amplifier is shown in fig. 6. The high gain is a result of the high Er concentration in the glass (5.3×10^{20} Er/cm^3), and the low co-operative upconversion coefficient, which is a result of the homogeneous Er distribution in this multi-component glass. Due to the relatively high index of the phosphate glass (n=1.56), a low pump threshold of only 7 mW could be achieved.

As becomes clear from the overview given above, at present two classes of materials have been successfully used to develop efficient planar Er-doped optical amplifiers. In silica-based glasses, waveguides have been made with very low losses, in the 0.1 dB/cm range. High optical gains (up to 27 dB) can be achieved, often only using relatively long waveguide structures. Silica-based waveguide amplifiers will be most useful in areas of integrated optics where size is less important than efficiency. Co-doping the silica with P_2O_5 leads to an increased refractive index, and hence better mode confinement. This, in combination with a low co-operative upconversion coefficient, has lead to the development of an amplifier with a gain of 4.1 dB over 1 cm at 21 mW pump power, the highest reported gain per unit length at low pump power. Ceramic thin films such as polycrystalline Al_2O_3 and Y_2O_3 have an even higher refractive index, allowing miniature devices (typical area 1 mm^2) to be made, ideally suited for use in Si-based integrated optical devices. Minimizing waveguide losses, and optimizing the local Er distribution in these materials in order to minimize co-operative upconversion is essential to further increase the achievable gain.

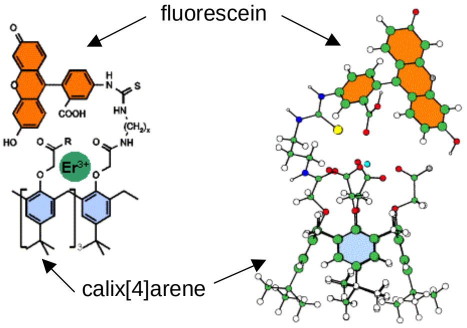

Figure 7: Schematic drawing (left) and a steric rendering (right) of an organic complex, calix[4]arene, doped with Er, with a fluorescein molecule attached (from Ref. 32). When fluorescein is excited optically around 490 nm, it can transfer its energy to the Er^{3+} ion. Due to the large absorption cross-section of fluorescein, this can enhance the effective Er excitation cross-section.

Outlook

Future research in Er-doped planar optical amplifiers will focus on further optimization of materials composition and device geometries, in order to increase the net gain, and reduce the pump power and device dimensions. Aside from research on glasses and ceramic materials, two other materials that can be integrated with Si are of great interest at this stage.

Polymers are interesting materials to use as optical waveguide materials. Their synthesis and processing is quite well developed. They can be deposited at relatively low temperatures (~200°C) using the low cost spin-coating process. Polymer based passive devices such as splitters, and thermo-optic switches are now commercially available. As a result of their relatively low index, polymer waveguides are easily coupled to standard silica glass fiber. Doping these polymer waveguide films with Er is not an easy task, as the commonly used rare earth salts are poorly soluble in a polymer matrix. To overcome this problem, Er ions can be incorporated in an organic complex,[31] that does dissolve in a polymer matrix. Using known supramolecular chemistry it is possible to add a sensitizer to the organic complex, which can serve to increase the absorption cross section. Figure 7 shows a schematic of a recently synthesized Er-doped calix[4]arene complex,[32] with a *fluorescein* sensitizer attached. These samples show photoluminescence at 1.54 µm, when excited into the fluorescein absorption band at 490 nm.[33] Research today focuses on studying the intra-molecular energy transfer in these complexes, and reducing the non-radiative processes that reduce the Er luminescence quantum efficiency.

Silicon itself would of course be the ideal host for integrated optical amplifiers in Si-based opto-electronics. Indeed, it has been shown that Si can be doped with optically active Er, using e.g. ion implantation[34-38] or molecular beam epitaxy techniques.[39,40] Erbium in Si can be excited not only optically, but also electrically, through an impurity Auger process in which electrical carriers transfer their recombination energy to Er. In principle, the latter would allow for electrical pumping of an Er-doped Si planar waveguide amplifier. However, several limitations have become clear in the past few years. First of all, the maximum optically active Er concentration that can be dissolved in single-crystal Si of high optical and electrical quality is limited to roughly 10^{20} Er/cm^3. Second, free carrier absorption in an (electrically pumped) Si waveguide will cause high waveguide losses. Thirdly, non-radiative quenching processes reduce the Er luminescence efficiency at room temperature. On the other hand, due to their high refractive index, Si waveguides have extremely well confined optical modes leading to efficient excitation. Si waveguides can be made with a bending radius as small as 1 μm, enabling the fabrication of devices with very small size.[41] Clearly, the development of an Er doped optical waveguide amplifier in Si would be an important step towards silicon based microphotonics, and more research is required - and already going on - in this area.[42]

Acknowledgements

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